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DESIGN AND OPERATING MODES OF STOP AND CONTROL VALVES OF HIGH-POWER STEAM TURBINES

The operating modes of stop and control valves of high-pressure and intermediate-pressure (low-pressure) sections of existing steam turbines of thermal and nuclear power plants are discussed in the article. Typical operating modes of the valves are defined depending on their functional purpose within the installation, the steam distribution system, the turbine type, and the method of power control. The flow pattern in angle-type valves with one side steam supply into the steam chest is discussed. It is noted that this design is typical for use in high-power steam turbine units operated in Ukraine. As a result, a classification of stop and control valves into three groups is proposed. For each group, recommendations are provided regarding the design of the valve flow-path elements, specifically the main plug and the seat, which contribute to improving their operational efficiency. In addition, to stabilize the flow, the feasibility of installing a special cylindrical shell inside the steam chest is considered, featuring an impermeable sector oriented toward the valve inlet pipe.

Key words: stop valve, control valve, governor valve, valve plug, steam distribution system, steam turbine.

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ОСОБЛИВОСТІ РЕЖИМІВ ЕКСПЛУАТАЦІЇ ТА КОНСТРУКТИВНОГО ВИКОНАННЯ СТОПОРНИХ ТА РЕГУЛЮЮЧИХ КЛАПАНІВ ПОТУЖНИХ ПАРОВИХ ТУРБІН

В статті наведено огляд режимів експлуатації стопорних та регулюючих клапанів циліндрів високого та середнього (або низького) тиску потужних паротурбінних установок теплових та атомних електростанцій. Визначені типові режими роботи клапанів в залежності від їх функціонального призначення у складі установки, в залежності від системи паророзподілу, типу турбіни та способа регулювання її потужності. Обговорюється структура течії в клапанах з конструкцією кутового типу з одностороннім бічним підведенням робочого тіла в парову коробку. Відмічено, що така конструкція є типовою у використанні у складі потужних паротурбінних установок, що експлуатуються в Україні. За результатами аналізу запропоновано розділення стопорних та регулюющих клапанів на три групи в залежності від діапазону їх роботи. Для кожної із груп наведені рекомендації щодо конструктивного виконання елементів проточного тракту клапана, зокрема основної запірної чаші та сідла, що сприяють підвищенню ефективності їх роботи. Також для стабілізації течії розглянуто доцільність встановлення спеціальної обічайки всередині парової коробки клапана, що має непроникний сектор, обернений до входу в клапан.

Ключові слова: стопорний клапан, регулюючий клапан, система паророзподілу, парова турбіна.

Introduction

Renewable energy sources tend to increase their share in modern energy systems. Meanwhile, the demand of wider ranges of maneuverability of conventional power-generating units of thermal (TPPs) and nuclear power plants (NPPs) increases [1], [2].

Changing or expanding the operating modes of the existing equipment may lead to instances of equipment instability. In particular, for the executive components of steam distribution system, control valves, manifestations of unsteady gas-dynamic forces acting on the main valve plug and stem, are often recorded. In some cases, excessive vibration levels of steam distribution elements occur, which leads to the premature depletion of their lifetime and requires limiting the operation of the turbine in the certain operating modes. Such cases require both modifications to the existing valve designs as well as their complete redesign [3] – [8].

When designing and optimizing modern stop (SVs) and control valves (CVs) of powerful steam turbines units (STUs), it becomes necessary to determine their operational modes, as well as possible limitations associated with the flow pattern formed in the flow path of valves.

The aim of the work

The aim of this work is to overview the operating modes of modern SVs and CVs of STUs and provide recommendations for their design both in the case of new equipment and for the existing equipment retrofit.

The general part

The main requirements for the control systems of TPPs and NPPs turbines, whose actuating mechanisms are SVs and CVs, are to provide reliable and trouble-free operation of STU in all modes of its operation while ensuring the minimum possible energy losses of the working fluid.

STU operational modes can be conditionally divided into two groups [3]:

1) Stationary (quasi) – at which the STU operates with a constant or relatively slow change in steam flow rate.

2) Transient – significant change in steam flow rate in a relatively short period of time.

The second group of STU operating modes includes: start-up, shut-down, idle mode, synchronization with the power grid and all emergency modes. The main indicator of control system effectiveness is its reliability and speed of response.

The first group includes load operating modes for the power grid, when the STU power changes in-significantly, or changes at the command of operator or control machine in accordance with the dispatch schedule of the electric grid loads. The control system for such cases operates in the following modes:

– pressure maintenance mode upstream STU;
– power grid frequency maintenance mode;
– electric power support mode;
– combined frequency and power support mode.

Nowadays, almost all TPPs and NPPs are involved in the power system schedule regulating. Analysis of daily grid schedules of thermal and electrical power consumption shows that during the night hours of the heating season, forced unloading at the TPPs power unit can reach 40 – 50 % of the installed electrical power at a thermal load of 80 – 100 %. Condensing type power units can be unloaded up to 30 – 40 % of their installed capacity during the night drops of consumption [3].

When STU operates in stationary modes, SVs of high-pressure cylinder (HPC), as well as SVs and CVs of intermediate-pressure cylinder (IPC) or low-pressure cylinder (LPC) operate with the stationary valve stem position. The main valve plug is lifted to the maximum height provided by the design and pressed tightly against the upper stop by the servomotor. The relative valve opening is in the range of $\bar{h}$ = 0.3 – 0.4. As a rule, this relative valve opening corresponds to the case when the minimum passage area is determined by the minimum internal diameter of the convergent-divergent type seat. The main plug almost has no effect on the mass flow rate throutput. The valve pressure ratio is about ε = 0.98 – 0.99, which corresponds to the subsonic flow regime in the entire flow path.

Design and retrofit of HPC SVs as well as IPC (LPC) SVs and CVs can be focused on one mode, which corresponds to the maximum stem lift and the maximum steam flow through it.

The operating conditions of HPC CVs in stationary modes are significantly differ. They are influenced by the type of steam distribution and by the electrical load controlling algorithm.

Fig. 1 shows data on the HPC CVs pressure ratio depending on the relative valve opening. The results are obtained during the aerodynamics calculations of nozzle steam distribution system of turbines operate with the constant inlet pressure upstream SVs [3].

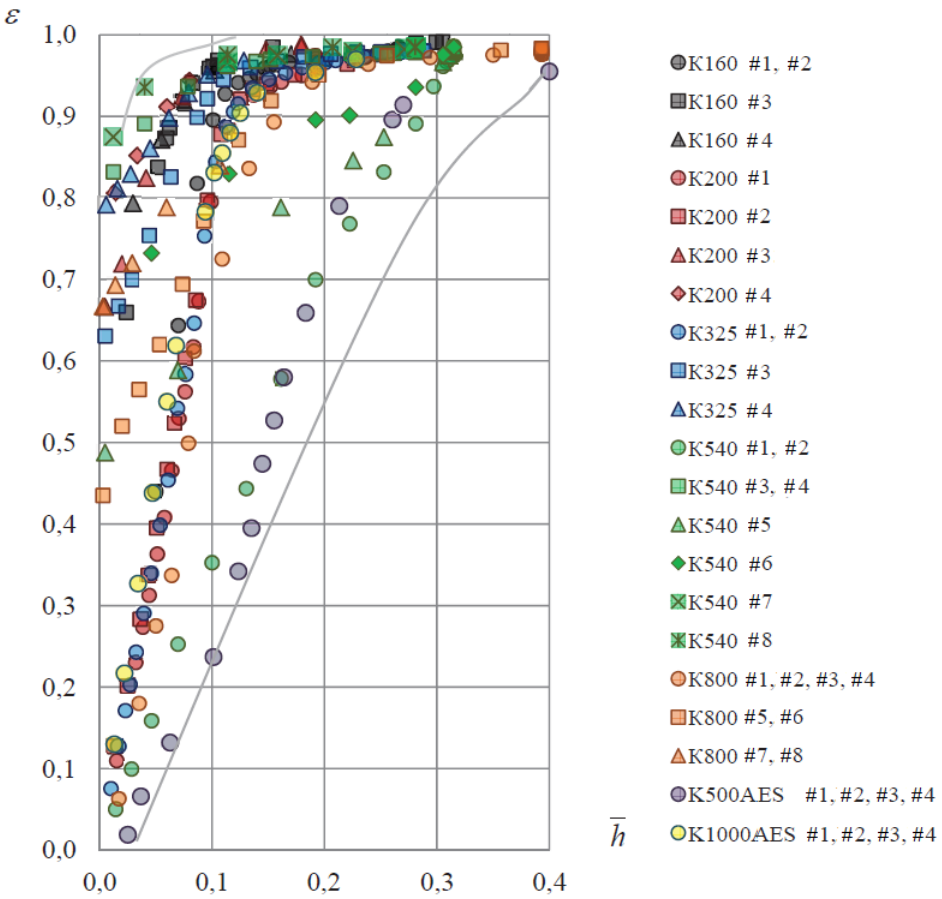

Fig. 1 – HPC CV pressure ratio depending on the relative valve opening [3] (operation with the fixed inlet pressure upstream SV)

Table 1 – Maximum relative valve opening HPC CVs [3]

Steam turbine	CV number			
	1	2	3	4
K-160-130 (Dobrotvir TPP, unit *8*)	0.267	0.267	0.305	0.170
K-200-130 (Kurakhiv TPP, unit *6*)	0.192	0.227	0.180	0.080
K-325-23.5 (Aksu TPP, unit *5*)	0.289	0.289	0.288	0.128
K-540-23.5 (Ekibastuz TPP, unit *2*)	0.315	0.281	0.315	0.281
K-800-240 (Sloviansk TPP, unit *7*)	0.393	0.393	0.393	0.107
K-220-44 (Kola NPP, unit *1*)	0.208	0.208	0.194	0.194
K-500-65/3000 (Kursk NPP, unit *1*)	0.403	0.403	0.403	0.403
K-1000-60/1500 (Balakovo NPP, unit *2*)	0.228	0.228	0.228	0.228
K-1000-60/3000 (Khmelnitsky NPP, unit *1*)	0.365	0.365	0.365	0.365

The statistical data on the maximum relative valve opening of HPC CVs of some existing high-power STUs of TPPs and NPPs are presented in Table 1 [3].

The data in Fig. 1 and in Table 1 refer to the design of angle-type valves with one-sided steam supply (Fig. 2), which is the most common in the equipment of power units in Ukraine.

The data in Fig. 1 presented in typical coordinates characterizing the flow coefficient φ (or valve performance): relative valve opening $\bar{h}$ and pressure ratio ε [3], [11]:

$$\varphi = \frac{G}{G_*} = f\left(\bar{h}, \varepsilon\right), \tag{1}$$

$$\bar{h} = \frac{h}{d}, \tag{2}$$

$$\varepsilon = \frac{p_2}{p_1^*}, \tag{3}$$

$$G_* = A_s \sqrt{p_1^* \rho_1^*} \sqrt{k \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}, \tag{4}$$

where h – main plug lift;

d – corrected diameter (as a rule, diameter of the valve plug seating on the seat, or the seat throat diameter);

p_2 – pressure downstream valve;

p_1^* – pressure upstream valve;

ρ_1^* – density, calculated by the inlet total parameters;

k – isentropic exponent.

The design with the throttle steam distribution system and the operation with the constant inlet pressure upstream SVs is used in NPPs STUs [3]. With this type of steam distribution, the electrical power controlling is carried out by the steam flow rate variation when CVs positioning.

The range of possible long-term operating modes of HPC CVs of NPPs depends on the permissible range of the nuclear reactor regulation. For STUs operate with WWER-440 and WWER-1000 reactors, the power controlling range can be about 70 – 80...100 % of the nominal power [3], [9], [10]. With a linear dependence of the steam flow rate on the stem movement, this corresponds to the lift of 70 – 100% of the maximum ($\bar{h}$ = 0.15 – 0.4) and to the pressure ratio on the valve ε = 0.70 – 0.98.

The design of the nozzle steam distribution with 4 nozzle segments, as a rule, is used in STUs of TPPs. Turbines can operate at either the constant or the “sliding” inlet pressure upstream SVs, depending on the boiler type.

A combined variant of the power units controlling may be used in case of the “sliding” pressure operation [3]. The operating algorithm depends on the control system design, plant equipment restrictions and must be determined individually for each STU based on technical-economic evaluations.

The algorithm is often used when operating at “sliding” pressure while all CVs are fully opened.

If there is an individual servodriver for each CV, an algorithm can be implemented where the power unit operates at a constant pressure in the load range close to the design point. Starting from a certain mode, some of the CVs are closed and the turbine is switched to operation at the “sliding” inlet pressure.

With such algorithm, the main part of CVs, as a rule, which serving the first three nozzle segments, operates over most of the power unit's control range. The changes in the stem positioning are minor as well as the pressure ratio variation. For this case, CVs operate like SV: relative valve opening is close to the maximum $\bar{h}$ = 0.2 – 0.4; high pressure ratio ε = 0.95 – 0.98.

Significant variations in the stem lift and in the pressure ratio have CVs of STUs operating at constant pressure upstream SVs. Considering possible range of long-term operation with the load up to 30 – 40 % of the nominal power, the range of the pressure ratio on the valve of segments No1, No2 and No3 can be ε = 0.30 – 0.98. And for CV No3 and No4, serving the 3th and 4th in order of working segments – from almost ε = 0 to ε = 0.90 – 0.98. The stem lift of CV No3 and CV No4 changes in the range from fully closed to maximum lift.

In general, for CVs of STUs with nozzle steam distribution, which operate with constant inlet pressure upstream SVs, the design point selection should be determined individually, considering the order of its entry into operation. But in practice, engineering companies strive for the components unification, which leads to the use of the same valve design for most, or all CVs. As a result, the desire to reduce the costs of engineering and manufacturing is opposed to the complexity of developing a design that ensures effective work over the entire wide range of operation.

When designing and retrofiting SVs and CVs, the requirements of the targed performance indicators of steam distribution should also be met. There are the flow rate and power characteristics of the STU depending on CVs lifts. Also, for stable operation of the control system, it is advisable to provide a linear dependence of the steam flow rate on the lift of the stem, which facilitates turbine control and contributes to the fulfillment of the requirements for the linearity of the static control characteristic. The force characteristic should be smooth and minimize the highest absolute steam force on the stem, as well as the difference between its maximum and minimum value.

Results discussion

Based on the overview, SVs and GVs can be divided into the following groups:

1) Valves with the fixed stem position.

This group includes HPC SVs, IPC (LPC) SVs, as well as IPC CVs.

As noted above, during the STU main operational range under load, these valves are in the stationary position and do not perform the function of the steam flow rate controlling. For this case, the main design focus is on the level of energy loss in the valve. Considerable attention when designing and retrofiting should be paid to the gas-dynamic optimization of the valve channel formed by the seat and the main plug.

2) Valves for the specific operational region.

This group can conditionally include valves that operate within a specific range of valve plug lifts and pressure ratios. These are primarily the HPC CVs of NPPs turbines, as well as the CVs of TPPs turbines, which are operated in a stationary position with the combined variant of STU power regulation with the "sliding" inlet pressure.

For this group of valves, along with the requirement to ensure the low level of energy losses, there is also the task of ensuring stable operation in the selected specific operating range. Key components in meeting these requirements are the main plug and the valve seat.

When the main plug positioning, the flow path geometry as well as the pressure distribution across the valve plug is varying, which significantly affects the flow pattern in the valve channel. Depending on the mode, the shape of the flow around the profile surface of the plug changes. The flow deflection by 90-degrees in the valve chest influences flow unevenness in the circumferential direction and the formation of paired vortices both in the steam chest region (Fig. 2*b*), and in the valve channel region (Fig. 2*c*). The presence of paired vortices and jet separation from the plug profile surface in the area downstream the minimum cross-section and, or in the diffuser seat, can lead to unsteady gas-dynamic forces formation that affect the moving elements of the valve. As a result of high-intensity unsteady loads, low-cycle fatigue of the valve stem occurs, which in most cases can lead to its damage.

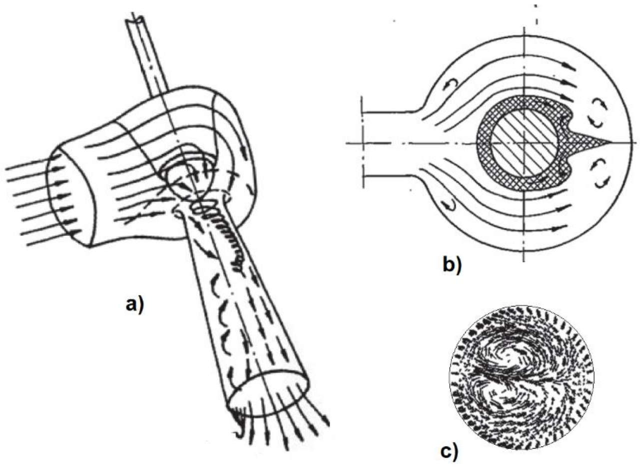

Fig. 2 – Flow pattern in the angle-type valve with one side steam supply:
a – general flow pattern in angle valve; *b* – valve chest section; *c* – seat minimal diameter section

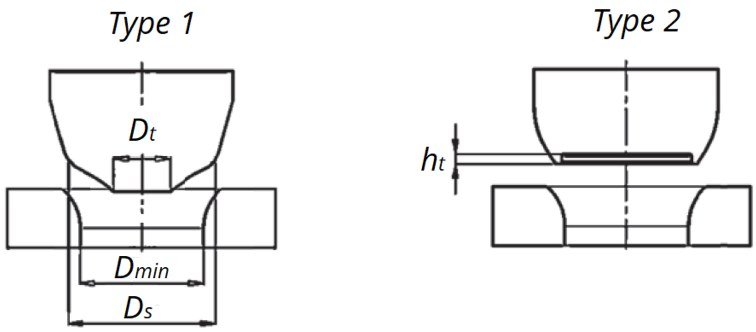

Fig. 3 – Geometrical parameters and shapes of the main plug;
type 1 – plug for valves of *Group 1* and *Group 2*; *type 2* – plug for valves of *Group 3*

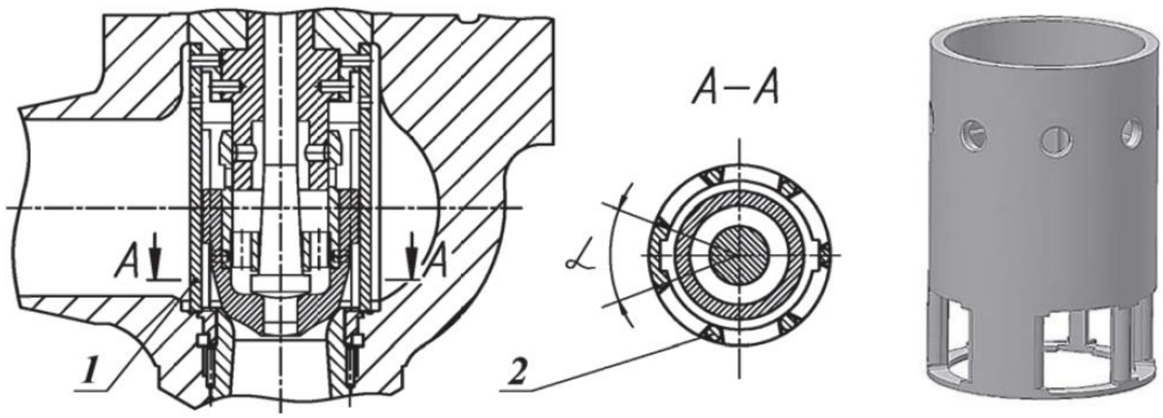

Fig. 4 – 200 MW turbine governor valve with the cylindrical shell:
1 – impervious sector; *2* – strut

The *type 1* of the main valve plug (Fig. 3) is recommended for this group of valves. The plug end-face trimming recommended is $D_t = (0.3 – 0.4)D_s$. The expansion angle of the convergent part of the valve seat is recommended not to exceed 7 deg. [3], [10].

3) Wide-mode valves.

This group includes CVs, which operate over the wide range of valve lift and pressure ratios.

The key issue for these valves is to ensure stable operation throughout the entire operating range.

One way is to use the main plug shape with a controlled jet separation point (Fig. 3, *type 2*) and ensure the single flow pattern in the valve channel. The plug end-face trimming recommended is $D_t = (0.9 – 0.95)D_s$, end-face recess of no less $h_t = (0.05 – 0.06)D_s$ [3].

To ensure stable operation, it is also recommended to increase steam load on the valve plug.

For existing valves with the steam force balanced system, a balance valve lift reduction is often used in case of unlimited vibration level. In some cases, this reduces the vibration level due to the pressed load increasing on the main plug. But it is not a universal method, since it does not eliminate the key problem – the unstable flow pattern in the valve channel.

One of the additional methods for stabilizing the flow and reducing energy losses in CVs of group *2* and *3* can be the cylindrical shell with the impermeable sector oriented toward the input pipe (Fig. 4) [3], [12], [13].

The cylindrical shell with the impermeable sector (30 – 60 deg) has a positive impact on the performance of valves with one-way side supply. The impermeable sector ensures a more uniform distribution of steam in the circumferential direction of the valve chest, which reduces the intensity of the steam paired vortices formed in the valve channel downstream the minimum cross section (Fig. 2*c*).

The impermeable sector can also be used in steam strainers of the combined stop-control valves [3], [4] to reduce unevenness around the valve channel.

Conclusions

The operating modes of SVs and CVs of STUs TPPs and NPPs were overviewed.

The existing valves are divided into three groups and recommendations for design and retrofit are provided:

Group 1 – valves operate with the fixed stem position: HPC SVs, IPC (LPC) SVs and CVs. Valves operate at the high relative opening $\bar{h}$ = 0.3 – 0.4 and pressure ratio ε = 0.98 – 0.99. Design and retrofit of such valves can be focused on the maximum steam flow rate mode. High attention should be paid to the aerodynamic quality of the valve channel formed by the main plug and valve seat.

Group 2 – valves for the specific operational range: HPC CVs of STUs NPPs; HPC CVs of STUs TPPs, which operate at the fixed stem position during the "sliding" pressure load regulation. The *type 2* of plug shape (Fig. 3) and the expansion angle of the convergent part of the valve seat that not exceed 7 deg are recommended for such valves.

Group 3 – wide-mode valves: HPC CVs of STUs TPPs, which operate with the fixed inlet pressure upstream CVs. The plug shape with the deep end low-face trimming is recommended for such valves. (Fig. 3, *type 2*).

The cylindrical shell with the impermeable sector oriented toward the input pipe is recommended as an additional option for the implementation. The impermeable sector 30 – 60 deg reduces the unevenness of parameters in the circumferential direction of the valve channel (Fig. 4).

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